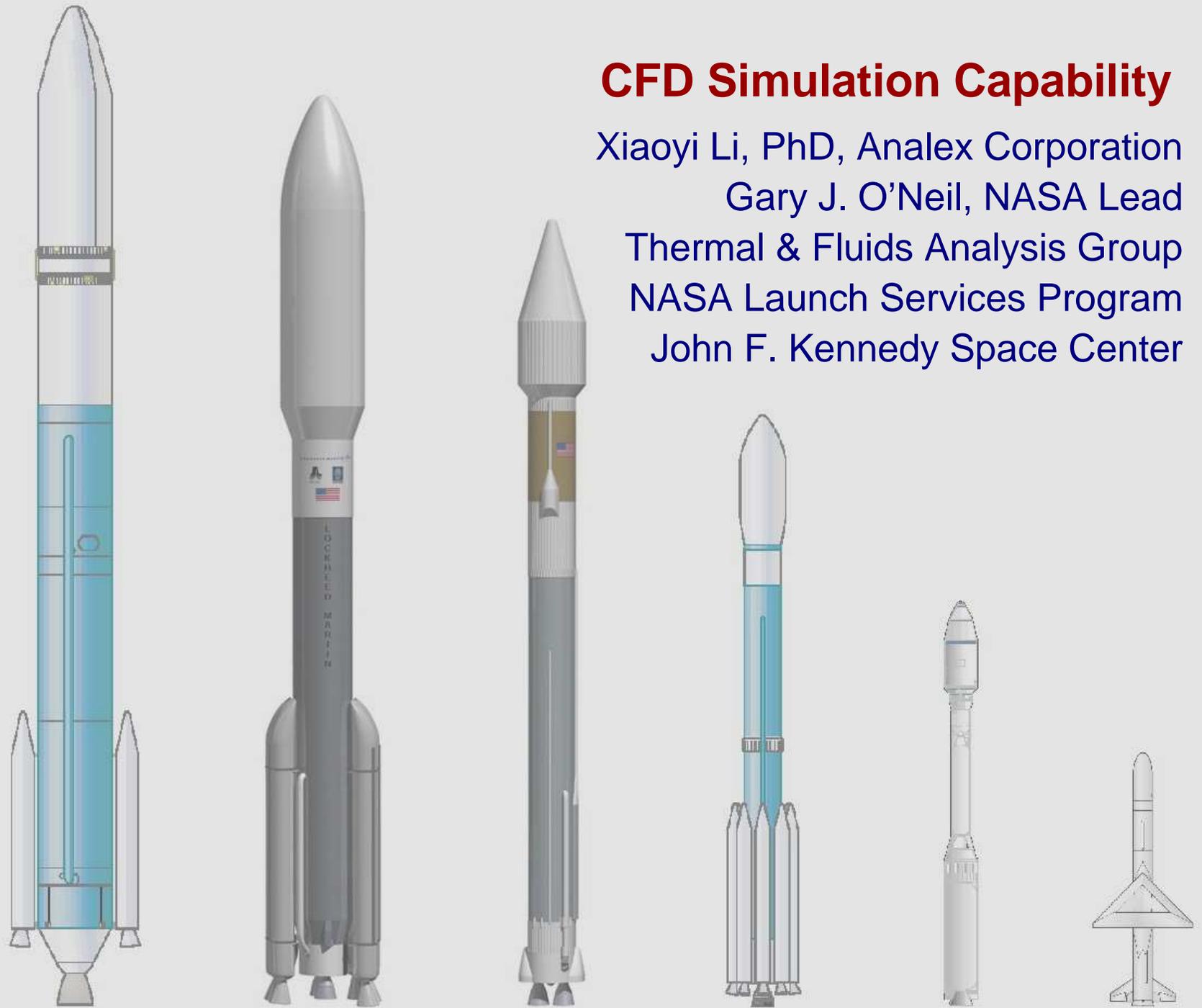




Launch Services Program

Thermal & Fluids Analysis Group



CFD Simulation Capability

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Thermal & Fluids Analysis Group

NASA Launch Services Program

John F. Kennedy Space Center

Content



- LSP Introduction
- Computational fluid dynamics capabilities overview
- Sample cases
 - Liquid fuel slosh
 - Lunar Lander plume study



Launch Services Program Introduction

Baseline Work

Fleet Insight
-Vehicle Enhancements
-Anomaly Resolution
-Post Flight Data Review

Mission Integration
-ICD Formulation & Verification
-Mission Unique Modifications
-Aeroheating Analysis
-Venting Analysis
-Integrated Thermal Analysis
-Launch Ops Support

Vehicle Certification
-Qualification review
-Independent Verification and
Validation (IV&V) analyses

Studies
-as funding becomes available
- collaboration with other Centers,
industry, academia



Computational Fluid Dynamics Capability at LSP

Launch Services Program

Thermal & Fluids Analysis Group

- Computational fluid dynamics (CFD) is commonly used to study thermal fluid problem. The CFD code solves continuity, momentum, energy equations using numerical methods.
- Problems solved using CFD at LSP
 - Liquid fuel slosh
 - Internal conjugate heat transfer
 - Exhaust plume impingement
 - External aerodynamics
- CFD code
 - Flow3D
 - Fluent
 - Overflow
 - USM3D

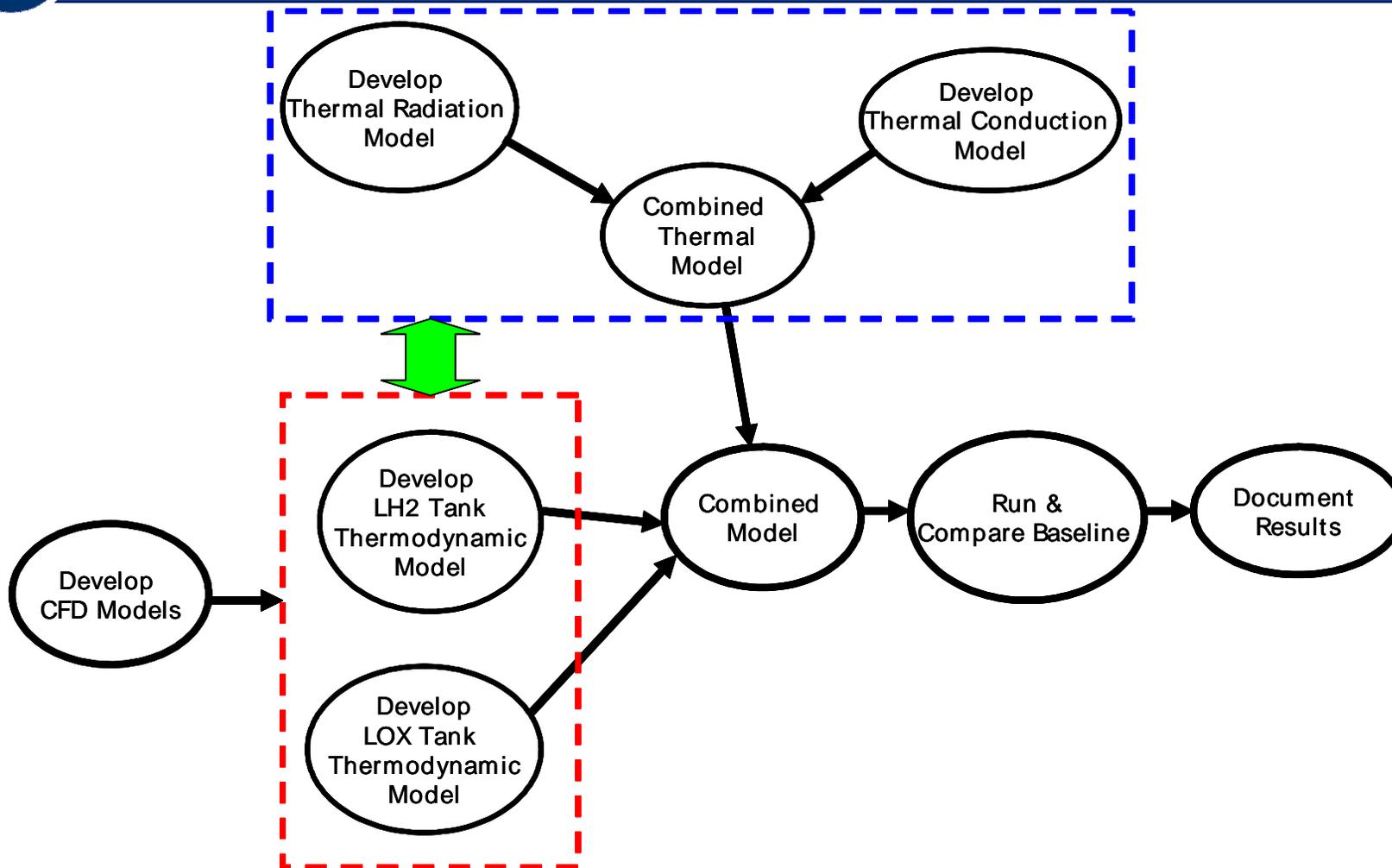


Example 1 – Liquid Fuel Slosh

- When the liquid fuel tank holds less fuel than full, the slosh dynamics plays an important role. This is critical especially when the gravity is small. Lack of body force, the fuel can be anywhere inside of the tank, and creates stability problem of the vehicle.
- In some mission, long coast with small amount of fuel in tank, the PTC roll can increase the contact surface area between wall and liquid fuel, as well as the interface between the ullage and liquid. Both can significantly increase heat transfer and fuel evaporation. Not mention, that slosh during the maneuver, liquid fuel quenches on the warmer wall, and evaporates instantaneously. Knowing how much fuel is evaporated is important to know the tank pressure and predict how much fuel left in the tank for the next start of engine.
- Fuel tank slosh was studied using commercial CFD code - FLOW3D.



Example 1 – Liquid Fuel Slosh (cont'd)





Example 1 – Liquid Fuel Slosh (cont'd)

- Parametric study with different acceleration rates ,fill levels and rotating speeds.
- Turbulent model: $k-\varepsilon$ model
- 4-DOF acceleration rates
- Predicted wetted wall area, and interface area between ullage and liquid fuel



Example 1 – Liquid Fuel Slosh (cont'd)

- Bond number: Ratio of the values of the surface forces to body forces. At higher altitudes it is thus possible to expect the surface tension force to become dominant.

$$B_o = \frac{F_g}{F_\sigma} = \frac{\rho g L^2}{\sigma}$$

If $Bo \approx 1$, the surface tension force is included in the model



Example 1 – Liquid Fuel Slosh (cont'd)

Analytical solution of the liquid interface:

$$h = \frac{\omega^2 r^2}{2g}$$

Interface area:

$$A_{\text{interface}} = \int_0^r 2\pi r ds$$

where $ds = \sqrt{1 + \left(\frac{dh}{dr}\right)^2} dr$

Therefore,

$$\frac{dh}{dr} = \frac{\omega^2 r}{g}$$

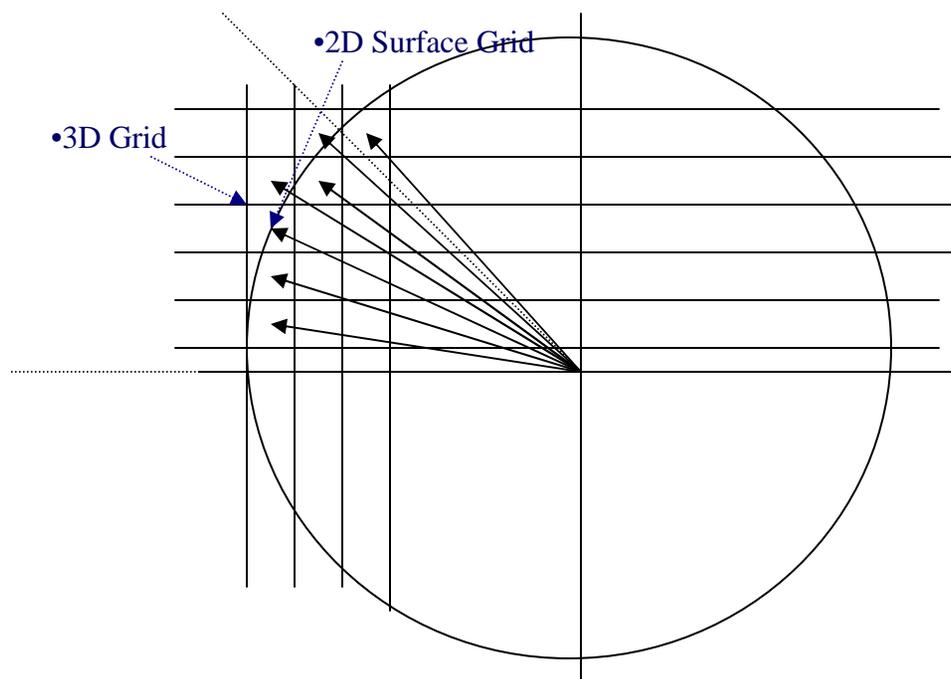
$$A_{\text{interface}} = \int_0^r 2\pi r \sqrt{1 + \left(\frac{\omega^2 r}{g}\right)^2} dr$$

Analytical solution is used to compute interface at higher bonds number, and to validate the CFD



Example 1 – Liquid Fuel Slosh (cont'd)

Mapping Scheme



Mapping uses sweeping method.

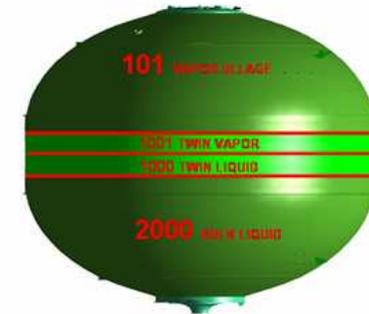
For each layer of the CFD grids, sweeps a bar from negative x-axis clock



Example 1 - Liquid Fuel Slosh (cont'd)



56	DOME	21000	184	21001	284	21002	384	21003	484	21004	584	21005	684	21006	784	21007	884	1
55	DOME	20800	184	20801	284	20802	384	20803	484	20804	584	20805	684	20806	784	20807	884	2
54	DOME	20600	184	20601	284	20602	384	20603	484	20604	584	20605	684	20606	784	20607	884	3
53	DOME	20400	184	20401	284	20402	384	20403	484	20404	584	20405	684	20406	784	20407	884	4
52	DOME	20200	184	20201	284	20202	384	20203	484	20204	584	20205	684	20206	784	20207	884	5
51	DOME	20000	184	20001	284	20002	384	20003	484	20004	584	20005	684	20006	784	20007	884	6
50	DOME	19800	184	19801	284	19802	384	19803	484	19804	584	19805	684	19806	784	19807	884	7
49	DOME	19600	184	19601	284	19602	384	19603	484	19604	584	19605	684	19606	784	19607	884	8
48	DOME	19400	184	19401	284	19402	384	19403	484	19404	584	19405	684	19406	784	19407	884	9
47	DOME	19200	184	19201	284	19202	384	19203	484	19204	584	19205	684	19206	784	19207	884	10
46	DOME	2519000	184	19001	284	2619002	384	19003	484	2719004	584	19005	684	2819006	784	19007	884	11
45	DOME	18800	184	18801	284	18802	384	18803	484	18804	584	18805	684	18806	784	18807	884	12
44	DOME	18600	184	18601	284	18602	384	18603	484	18604	584	18605	684	18606	784	18607	884	13
43	DOME	18400	184	18401	284	18402	384	18403	484	18404	584	18405	684	18406	784	18407	884	14
42	DOME	18200	184	18201	284	18202	384	18203	484	18204	584	18205	684	18206	784	18207	884	15
41	DOME	18000	184	18001	284	18002	384	18003	484	18004	584	18005	684	18006	784	18007	884	16
40	DOME	17800	184	17801	284	17802	384	17803	484	17804	584	17805	684	17806	784	17807	884	17
39	DOME	2117600	184	17601	284	2217602	384	17603	484	2317604	584	17605	684	2417606	784	17607	884	18
38	DOME	17400	184	17401	284	17402	384	17403	484	17404	584	17405	684	17406	784	17407	884	19
37	DOME	17200	184	17201	284	17202	384	17203	484	17204	584	17205	684	17206	784	17207	884	20
36	DOME	17000	184	17001	284	17002	384	17003	484	17004	584	17005	684	17006	784	17007	884	21
35	CYLINDER	16800	184	16801	284	16802	384	16803	484	16804	584	16805	684	16806	784	16807	884	1
34	CYLINDER	16600	184	16601	284	16602	384	16603	484	16604	584	16605	684	16606	784	16607	884	2
33	CYLINDER	16400	184	16401	284	16402	384	16403	484	16404	584	16405	684	16406	784	16407	884	3
		22100		22101		22102		22103		22104		22105		22106		22107		
32	CYLINDER	16200	184	16201	284	16202	384	16203	484	16204	584	16205	684	16206	784	16207	884	4
31	CYLINDER	16000	184	16001	284	16002	384	16003	484	16004	584	16005	684	16006	784	16007	884	5
30	CYLINDER	15800	184	15801	284	15802	384	15803	484	15804	584	15805	684	15806	784	15807	884	6
29	CYLINDER	15600	184	15601	284	15602	384	15603	484	15604	584	15605	684	15606	784	15607	884	7
28	CYLINDER	15400	184	15401	284	15402	384	15403	484	15404	584	15405	684	15406	784	15407	884	8
27	CYLINDER	15200	184	15201	284	15202	384	15203	484	15204	584	15205	684	15206	784	15207	884	9
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25	CYLINDER	14800	184	14801	284	14802	384	14803	484	14804	584	14805	684	14806	784	14807	884	11
24	CYLINDER	14600	184	14601	284	14602	384	14603	484	14604	584	14605	684	14606	784	14607	884	12
23	CYLINDER	14400	184	14401	284	14402	384	14403	484	14404	584	14405	684	14406	784	14407	884	13
22	CYLINDER	14200	184	14201	284	14202	384	14203	484	14204	584	14205	684	14206	784	14207	884	14
21	DOME	14000	184	14001	284	14002	384	14003	484	14004	584	14005	684	14006	784	14007	884	1
20	DOME	13800	184	13801	284	13802	384	13803	484	13804	584	13805	684	13806	784	13807	884	2
19	DOME	13600	184	13601	284	13602	384	13603	484	13604	584	13605	684	13606	784	13607	884	3
18	DOME	913400	184	13401	284	1013402	384	13403	484	1113404	584	13405	684	1213406	784	13407	884	4
17	DOME	13200	184	13201	284	13202	384	13203	484	13204	584	13205	684	13206	784	13207	884	5
16	DOME	13000	184	13001	284	13002	384	13003	484	13004	584	13005	684	13006	784	13007	884	6
15	DOME	12800	184	12801	284	12802	384	12803	484	12804	584	12805	684	12806	784	12807	884	7
14	DOME	12600	184	12601	284	12602	384	12603	484	12604	584	12605	684	12606	784	12607	884	8
13	DOME	12400	184	12401	284	12402	384	12403	484	12404	584	12405	684	12406	784	12407	884	9
12	DOME	12200	184	12201	284	12202	384	12203	484	12204	584	12205	684	12206	784	12207	884	10
11	DOME	512000	184	12001	284	612002	384	12003	484	712004	584	12005	684	812006	784	12007	884	11
10	DOME	11800	184	11801	284	11802	384	11803	484	11804	584	11805	684	11806	784	11807	884	12
9	DOME	11600	184	11601	284	11602	384	11603	484	11604	584	11605	684	11606	784	11607	884	13
8	DOME	11400	184	11401	284	11402	384	11403	484	11404	584	11405	684	11406	784	11407	884	14
7	DOME	11200	184	11201	284	11202	384	11203	484	11204	584	11205	684	11206	784	11207	884	15
6	DOME	11000	184	11001	284	11002	384	11003	484	11004	584	11005	684	11006	784	11007	884	16
5	DOME	10800	184	10801	284	10802	384	10803	484	10804	584	10805	684	10806	784	10807	884	17
4	DOME	10600	184	10601	284	210602	384	10603	484	310604	584	10605	684	410606	784	10607	884	18
3	DOME	10400	184	10401	284	10402	384	10403	484	10404	584	10405	684	10406	784	10407	884	19
2	DOME	10200	184	10201	284	10202	384	10203	484	10204	584	10205	684	10206	784	10207	884	20
1	DOME	10000	184	10001	284	10002	384	10003	484	10004	584	10005	684	10006	784	10007	884	21
	FIRST	1000	200	300	400	500	600	700	800									BOTTOM
	LAST	1056	256	356	456	556	656	756	856									TOP



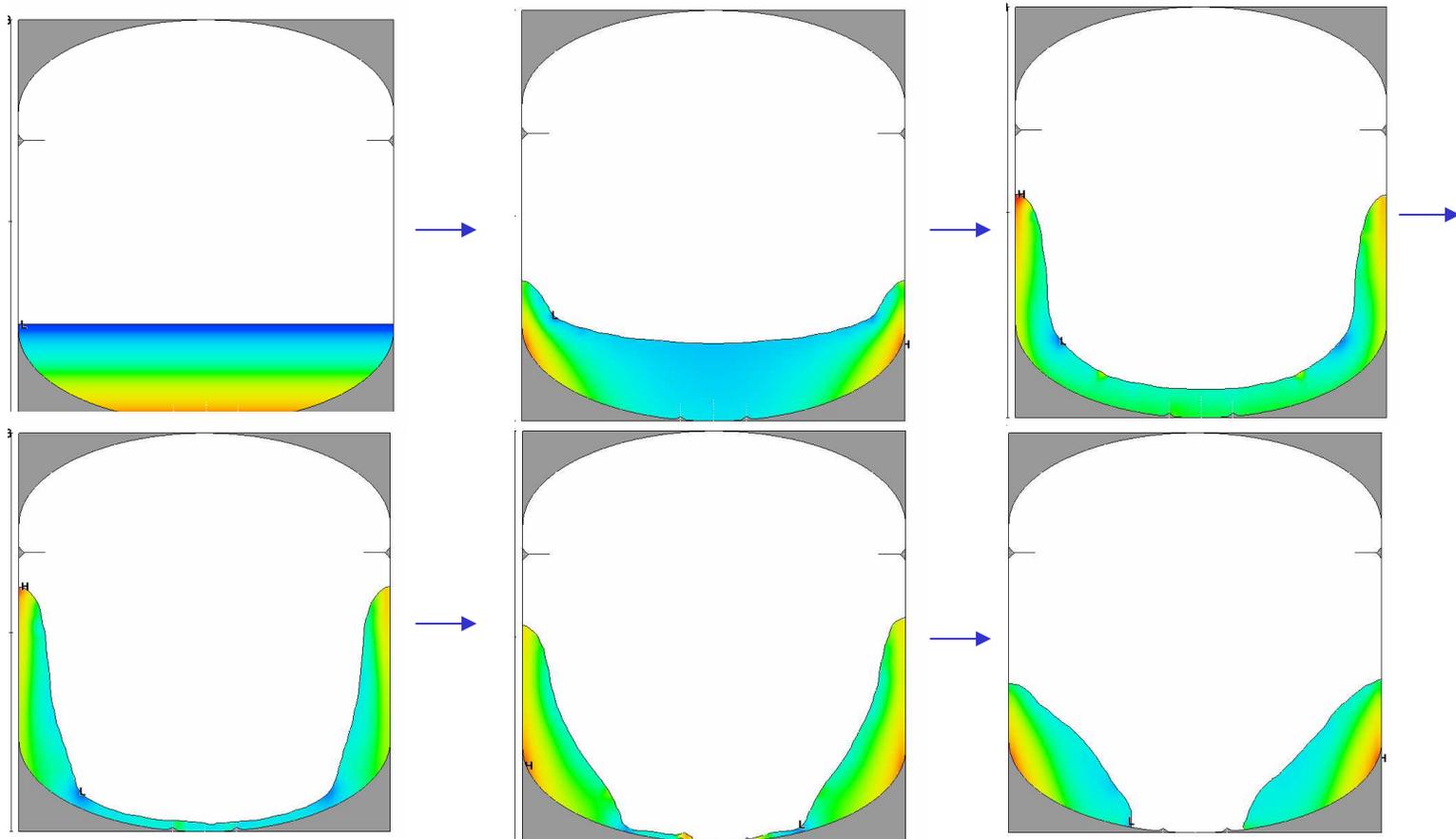
Mapping 3D CFD solution to 2D thermal nodes.

CFD grids are 3-dimensional, but thermal nodes are 2-dimensional.



Example 1 – Liquid Fuel Slosh (cont'd)

Plot of Pressure

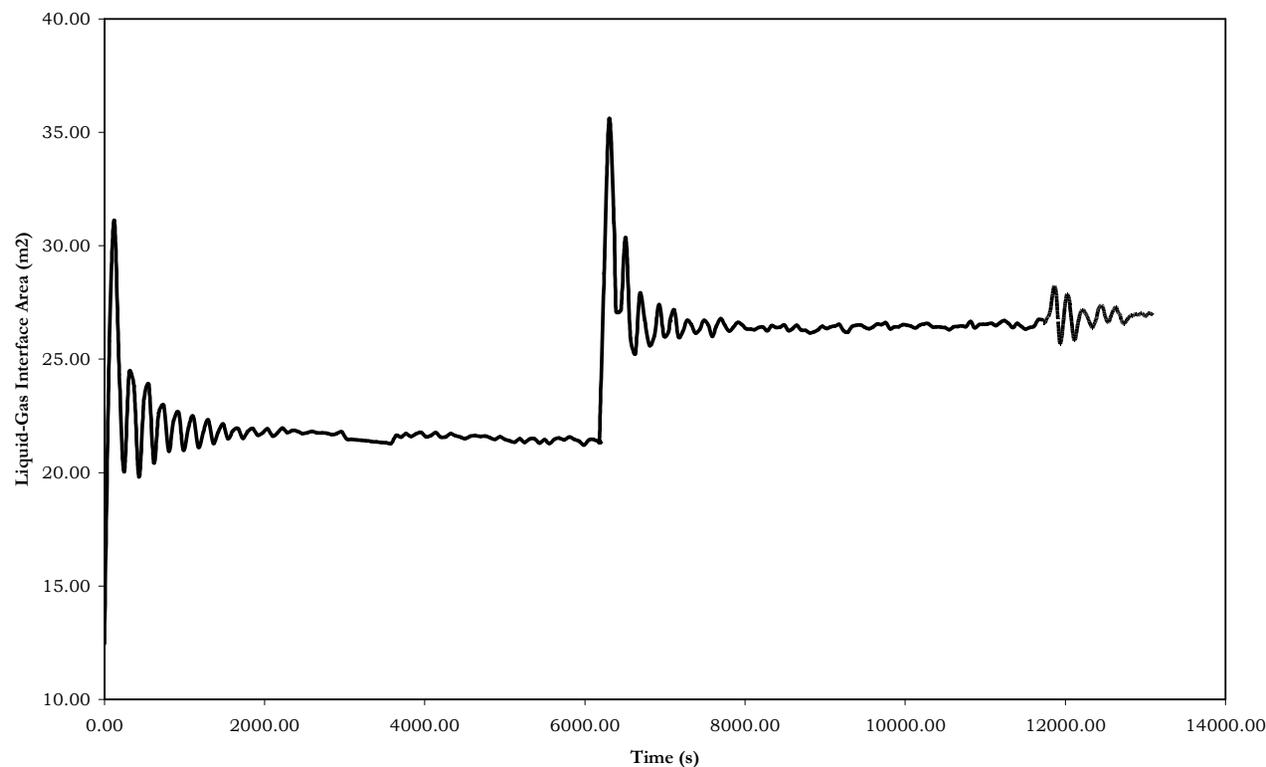


Change of interface shape during spin-up.



Example 1 – Liquid Fuel Slosh (cont'd)

Liquid-Gas interface area vs. Time (LH2)

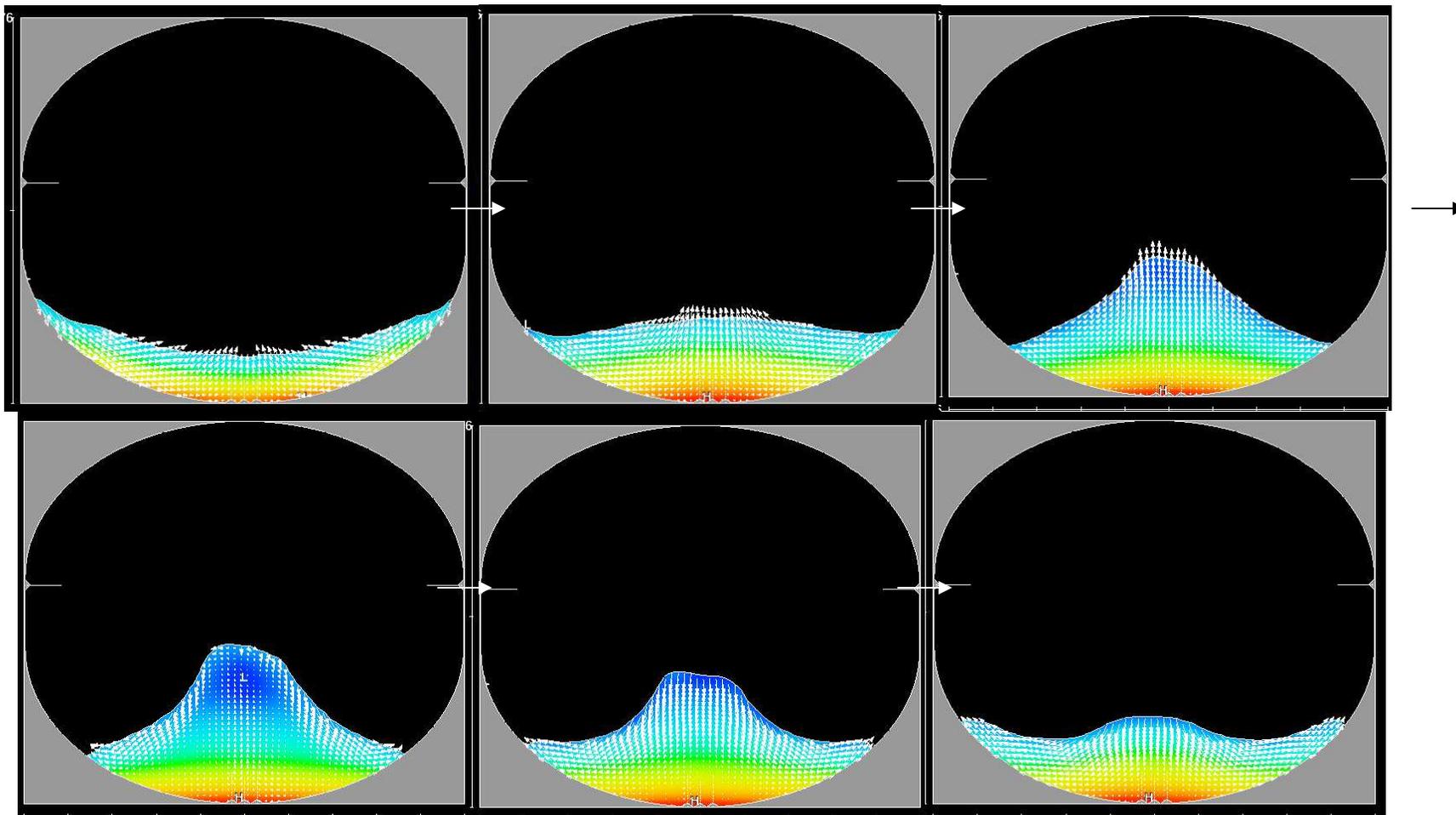


The interface area oscillates while changing the direction of rotation.

The first change of rotation used re-start, but the second one ran continu



Example 1 – Liquid Fuel Slosh (cont'd)



Fuel slosh due to change of the linear acceleration. (accelera



Example 2 – Lunar Surface Plume Impingement



Example 2 – Lunar Surface Plume Impingement (cont'd)



- Particle Ballistic Study of Lunar Dust Particles
 - Purpose of the study
 - Supersonic jet of exhaust plume accelerates dust, soil, gravel, and small rocks on lunar surface to high velocities.
 - Low gravity and close to vacuum environment on lunar surface allows the particles to travel at the great distance unimpeded.
 - The sizes and kinetic energies of the particles can cause damage to the spacecraft and surrounding facilities.

Example 2 – Lunar Surface Plume Impingement (cont'd)



CFD (Computation Fluid Dynamics)

Particle Ballistics Simulation

Gas:

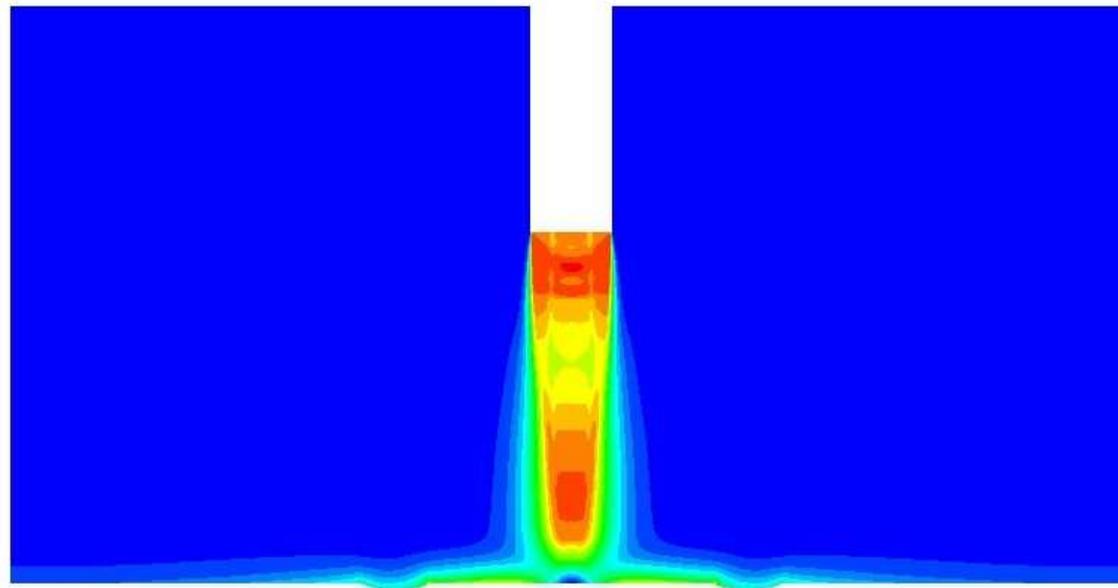
- *Density*
- *Velocity*
- *Temperature*

Particle:

- *Forces*
- *Acceleration*
- *Velocity*
- *Position*

CFD simulation predicts pressure, temperature and gas velocity on the surface directly under the nozzle and immediate surroundings.

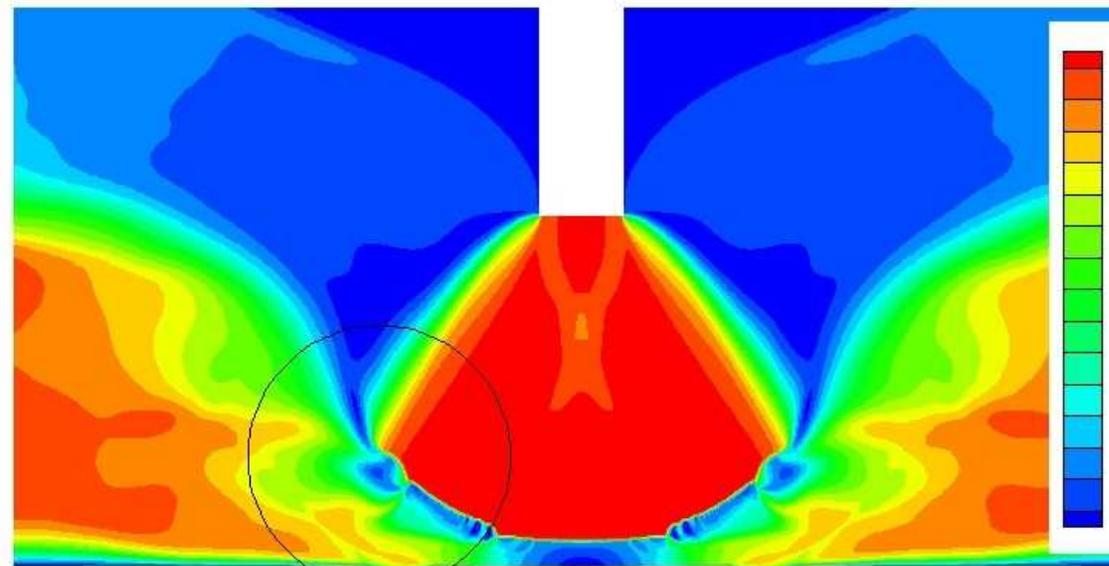
Example 2 – Lunar Surface Plume Impingement (cont'd)



Velocity Magnitude
Operating Pressure: 1 atm
Initial Pressure: 0 atm
Exit Pressure: 0 atm

Plume impingement in 1 atm environment.

Example 2 – Lunar Surface Plume Impingement (cont'd)



Velocity Magnitude
Operating Pressure: 1 Pascal
Initial Pressure: 0 Pascal
Boundary Condition at Exit: 0 Pascal

Flow interaction

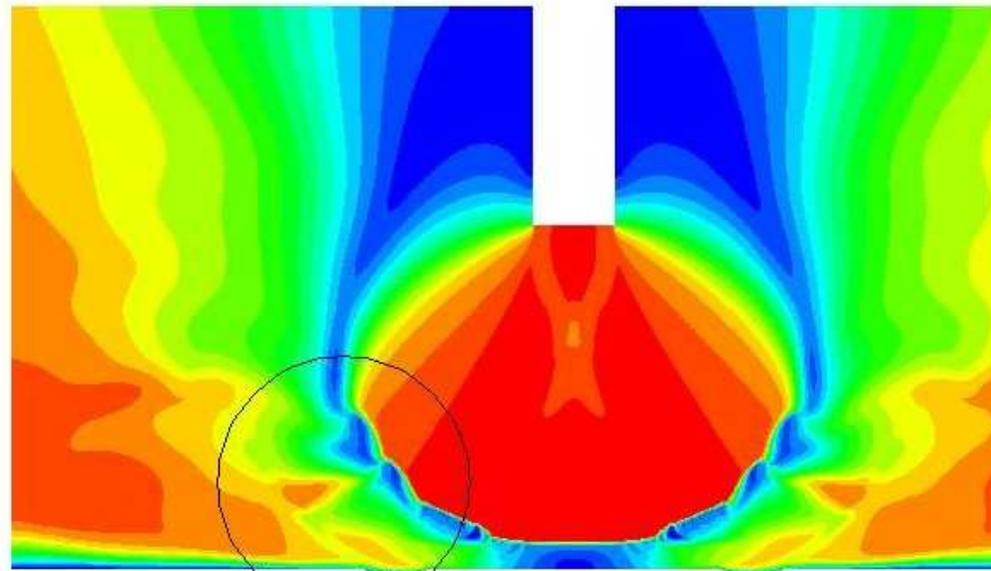
Plume impingement in 1 Pascal environment.

Example 2 – Lunar Surface Plume Impingement (cont'd)



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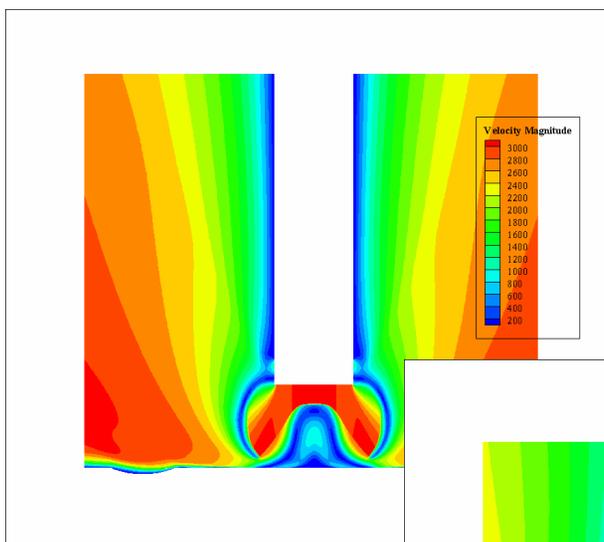


Flow Interaction

Velocity Magnitude
Operating Pressure: 0.1 Pascal
Initial Pressure: 0 Pascal
Exit Pressure: 0 Pascal

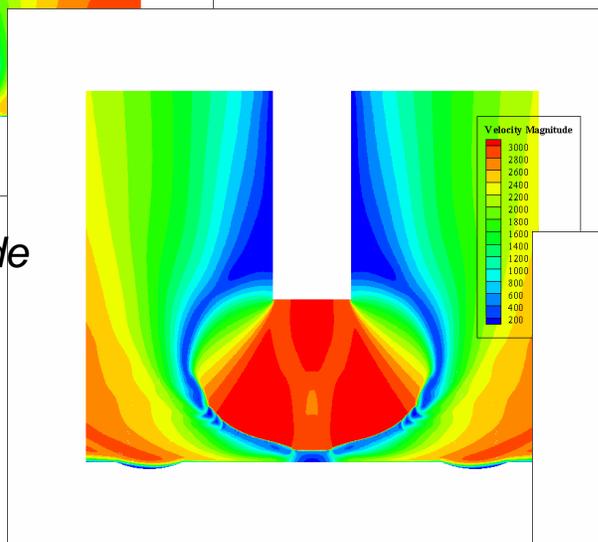
Plume impingement in 0.1 Pascal environment.

Example 2 – Lunar Surface Plume Impingement (cont'd)

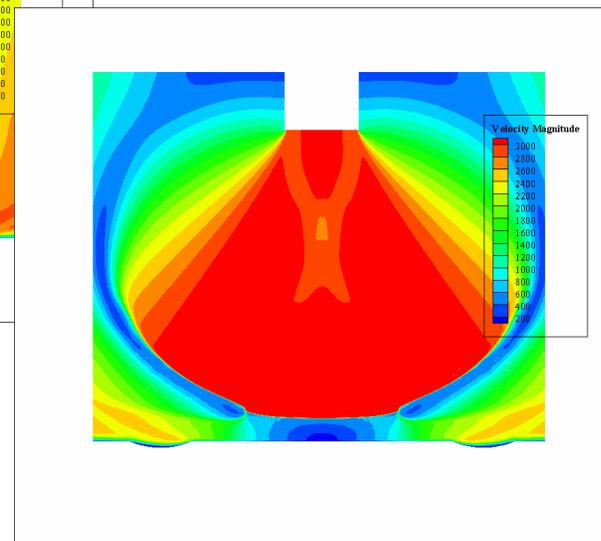


Recirculation zone under the nozzle at lower altitude.

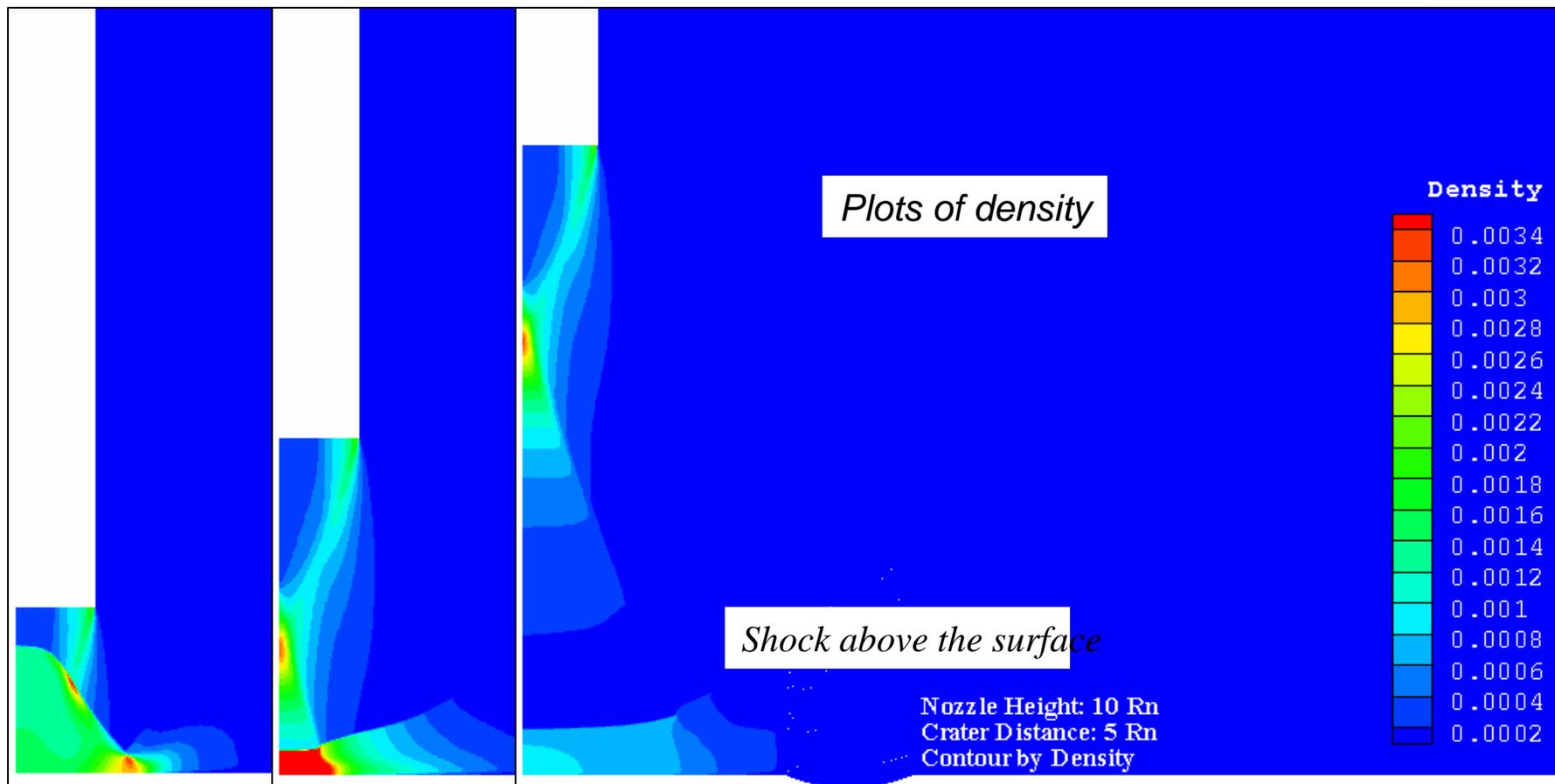
Plots of Velocity Magnitude



Plume impingement at different height.



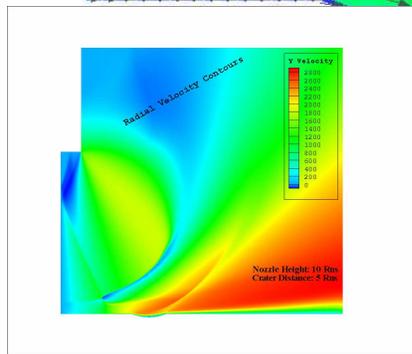
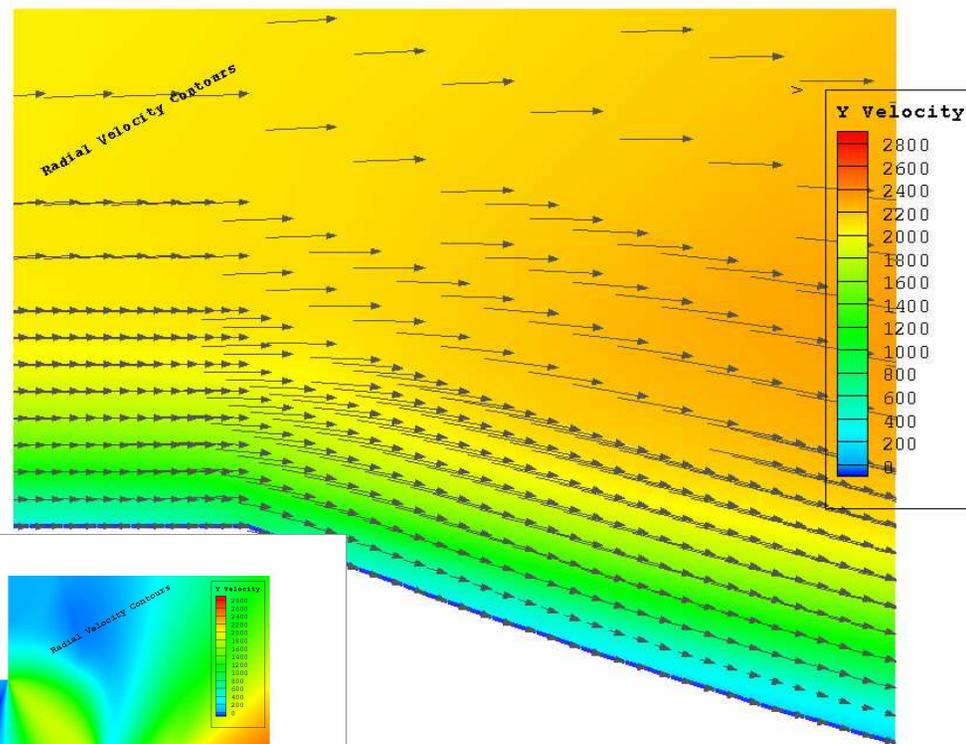
Example 2 – Lunar Surface Plume Impingement (cont'd)



Example 2 – Lunar Surface Plume Impingement (cont'd)



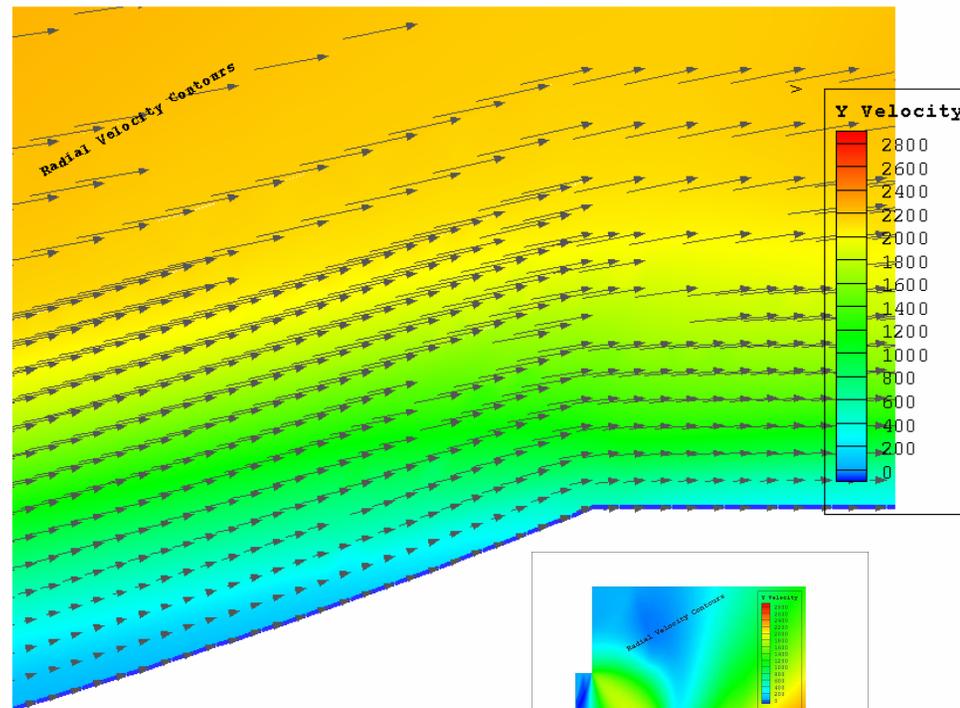
Effect of Crater on the Surface- Flow entering the crater



Example 2 – Lunar Surface Plume Impingement (cont'd)



Effect of Crater on the Surface- Flow leaving the crater

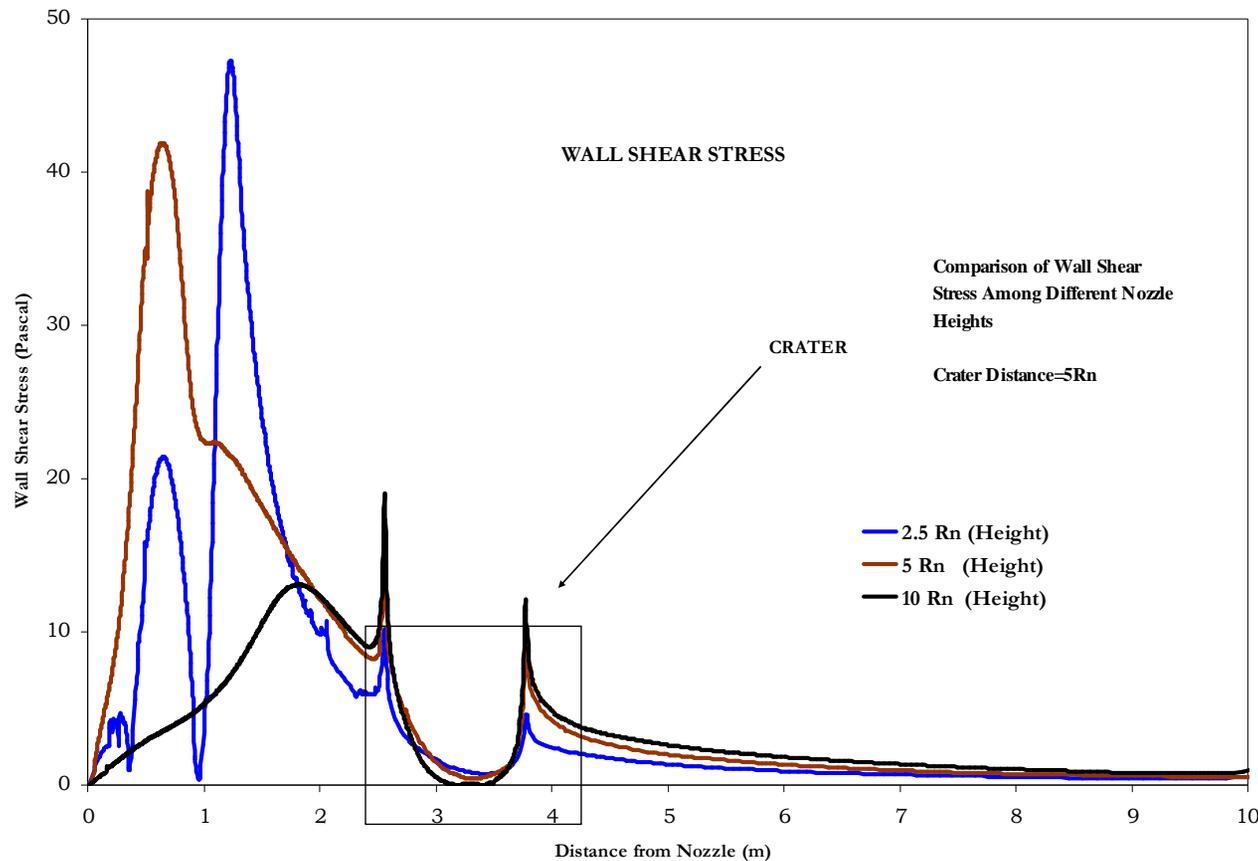


Flow separates from the main flow and forms a secondary jet.

Example 2 – Lunar Surface Plume Impingement (cont'd)



Plot of Shear Stress with Nozzle at Different Heights



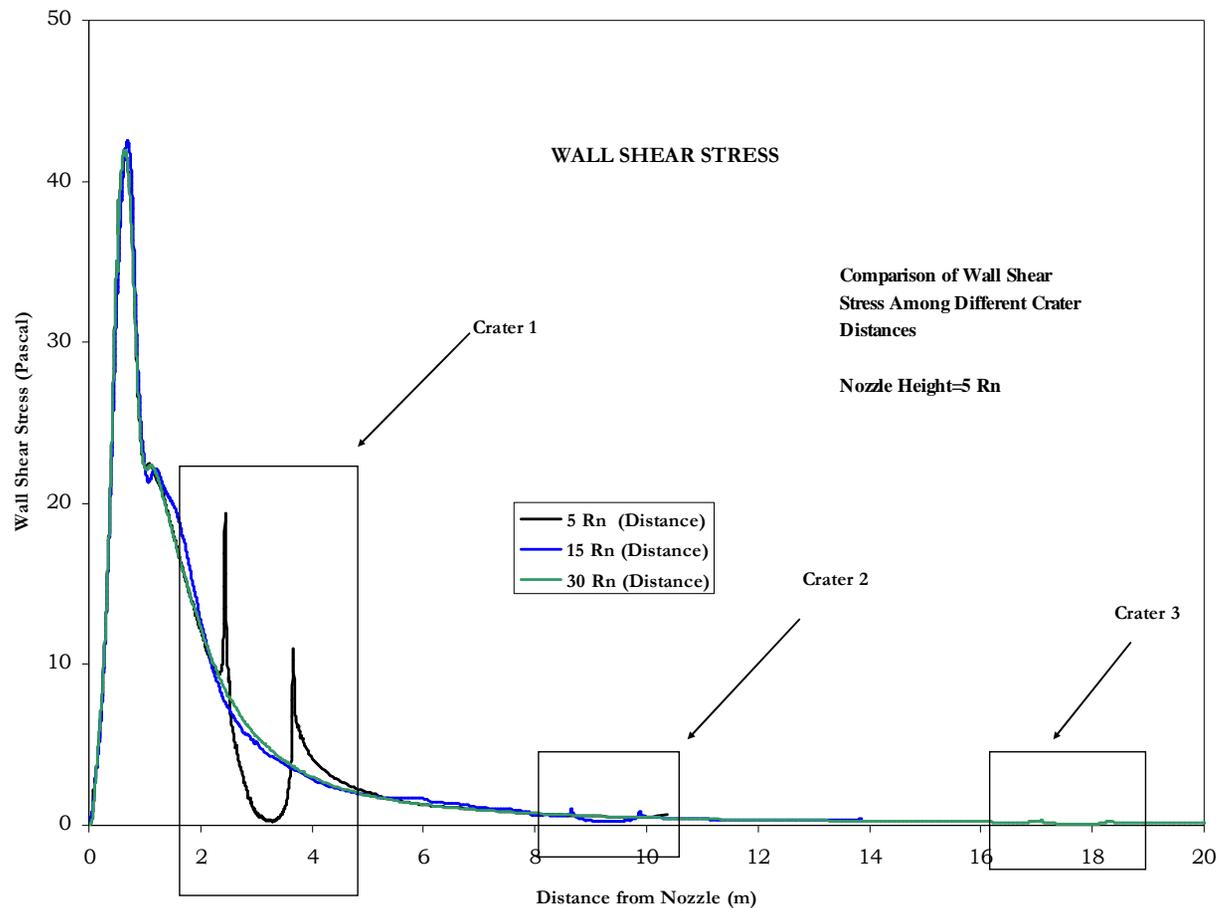
The lower the nozzle, the pick shear stress is larger.

The higher the nozzle, the shear stress on the surface and around crater is higher.

Example 2 – Lunar Surface Plume Impingement (cont'd)



Plot of Shear Stress with Craters at Different Distances from Nozzle



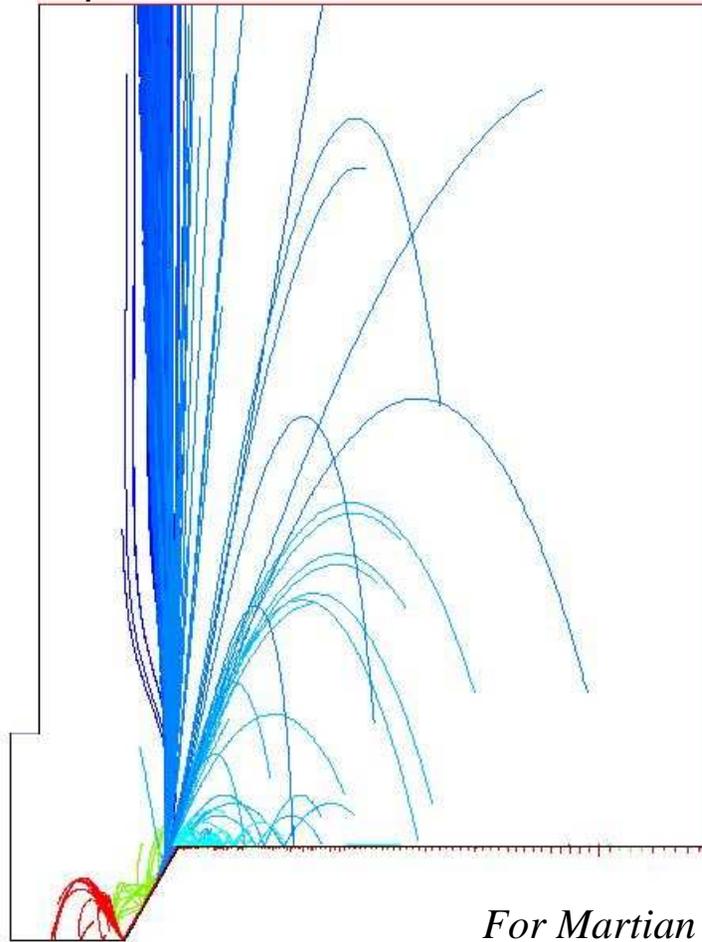
The closer the crater to the nozzle, the crater has more effect on the shear stress.

The crater doesn't affect the shear stress down stream of the crater.

Example 2 – Lunar Surface Plume Impingement (cont'd)



*Sample of Particle Trajectories
Colored by size of particles*



For Martian Plume Study



Future work

- Fuel tank slosh
 - Structure Load
 - Predict pressure on the tank wall due to the fuel slosh
 - Solving control problem
 - Predict instability of vehicle caused by slosh dynamics of the fuel
- Martian plume study
 - 2D axisymmetric (completed)
 - 3D three and four nozzles configurations (in progress)
 - LES turbulence model